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MULTI-PARTICLE CORRELATION AMONG GREY PARTICLES EMITTED IN NUCLEUS-NUCLEUS INTERACTIONS

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The short range correlation among emitted knock on nucleons from heavy ion collisions is used to reveal the dynamic characteristics of the reactions at high energy. Two- and three-particle correlations are considered in angular space to explain the emission of gray particles from collectively excited states of the nucleus as a Fermi liquid drop. Positive correlation is detected only among particles emitted in the extreme backward direction which is the coldest domain. It is interpreted as direct non-statistical emission (splashing) of nucleons via the dynamical distortion of the Fermi surface accompanying the collective motion.

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1. *Introduction*

In previous articles [1, 2], we demonstrated a model that describes the emission of gray particles based on a thermodynamic picture. The assumption of local equilibrium as well as the concept of the canonical ensemble could explain the formation of the non-equilibrium thermodynamic nuclear matter in phase space. The formed highly-excited nuclear system is divided into sub-domains, and each sub-domain was characterized by a local characteristic temperature. The superposition of spectra emitted from different domains in the energy range $40 \leq E \leq 400$ MeV describes the gray particle emission. The question arising now wraps around the dynamic effects acting on or playing a role in the process of the emission of the gray particles from the nuclear system. The default strategy leans on the correlation technique. The influence of short-range correlations in the angular distribution of nucleons emitted from nuclei can be evaluated assuming realistic dynamic effects. Many properties of nuclei could be understood within the independent particle model, where the nucleus is considered as a system of nucleons moving without residual interaction in a mean field or a single particle potential. But the short range of the strong nuclear forces and other tensor components that induce NN correlations in nuclear wave functions cannot be described by the independent particle model or even by the Hartree-Fock approach. Various tools have been developed to account for these strong short-range correlations. These include variational calculations assuming Jastrow correlation functions [3], the correlated basis function method (CBF) [4], the exponential S method [5], the Brueckner-Hartree-Fock (BHF) approximation [6] and the self- consistent Green function approach [7]. In the present work, we deal with the problem using the two-particle and the three-particle correlation functions, searching for a true signal in the angular space of the emitted nucleons that can express the presence of a dynamic effect.

2. Experimental work

A stack of the size 20 cm × 10 cm × 600 μm (undeveloped) was exposed to the beams of ^{24}Mg nuclei at momentum of 4.5 A GeV/c. The stack was irradiated by a beam oriented parallel to the length of the stack at the Dubna Synchrophasotron (Russia). The grain density, the blob density and the lacunarity [8] of the emitted particles were measured and classified into shower (s), grey (g) and black (b) particles [9]. The charge and the mass of the emitted particles were identified by several measurements, grain density-momentum, δ ray − energy measurements etc. In this work, we are interested mainly in the g-particles. The energy of the g-particles [10] was found either by the range measurement or by the Coulomb multiple scattering technique. A special computer program called SRIM [11, 12], is used to calculate the stopping power and estimate the range of the ions in the energy range (10 eV - 2 GeV/amu) through emulsion material using a full quantum mechanical treatment of ion-atom (medium) collisions. The space angles of the identified singly-charged gray particles were measured with tolerance less than 0.1°.

3. Short range correlations

A two-particle correlation function is defined as

$$R(z_1, z_2) = \left(\frac{1}{\sigma_{\rm in}} \frac{\mathrm{d}^2\sigma}{\mathrm{d}z_1 \mathrm{d}z_2} - \frac{1}{\sigma_{\rm in}^2} \frac{\mathrm{d}\sigma}{\mathrm{d}z_1} \frac{\mathrm{d}\sigma}{\mathrm{d}z_2} \right) \Big/ \left(\frac{1}{\sigma_{\rm in}^2} \frac{\mathrm{d}\sigma}{\mathrm{d}z_1} \frac{\mathrm{d}\sigma}{\mathrm{d}z_2} \right), \tag{1}$$

where $\sigma_{\rm in}$, $\frac{\mathrm{d}\sigma}{\mathrm{d}z_1}$ and $\frac{\mathrm{d}^2\sigma}{\mathrm{d}z_1 \mathrm{d}z_2}$ are the inelastic cross-section, the single- and the two-particle distributions, respectively, z_1 and z_2 are the values of a certain physical quantity corresponding to the two particles. The correlation function measures the dependence of the production of the two particles on their own characteristic parameters. The positive value of $R(z_1, z_2)$ means that the presence of one particle with a parameter Z_1 compels the existence of the other within Z_2. A zero value of $R(z_1, z_2)$ means that their emission is independent. On the other hand, a negative value of the correlation function means that the emission of particle at Z_1 excludes the emission of the other within Z_2. The normalized inclusive correlation function can be written for the case $z = \cos z$ as

$$R(\cos\theta_1, \cos\theta_2) = \tag{2}$$
$$\left(\frac{1}{\sigma_{\rm in}}\frac{{\rm d}^2\sigma}{{\rm d}\cos\theta_1{\rm d}\cos\theta_2} - \frac{1}{\sigma_{\rm in}^2}\frac{{\rm d}\sigma}{{\rm d}\cos\theta_1}\frac{{\rm d}\sigma}{{\rm d}\cos\theta_2}\right)\Big/\left(\frac{1}{\sigma_{\rm in}^2}\frac{{\rm d}\sigma}{{\rm d}\cos\theta_1}\frac{{\rm d}\sigma}{{\rm d}\cos\theta_2}\right),$$
$$= \frac{NN_2(\cos\theta_1, \cos\theta_2)}{N_1(\cos\theta_1)N_1(\cos\theta_2)} - 1$$

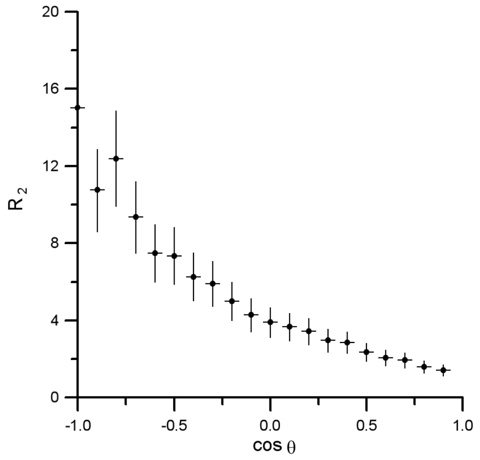
where $N_1(\cos\theta_1)$ is the number of interactions having a gray particle between $\cos\theta_1$ and $\cos\theta_1 + {\rm d}\cos\theta_1$ $N_2(\cos\theta_1, \cos\theta_2)$ is the number of interactions having at least two grey particles, the first with angle between $\cos\theta_1$ and $\cos\theta_1 + {\rm d}\cos\theta_1$, and the other of angle between $\cos\theta_2$ and $\cos\theta_2 + {\rm d}\cos\theta_2$ and N is the total number of investigated inelastic interactions. The error in measuring the correlation function $R(\cos\theta_1, \cos\theta_2)$ is a compound error [13, 14] that depends on the statistical errors ΔN, ΔN_1 and ΔN_2.

By analogy, the three particle correlation function is defined as

$$R(\cos\theta_1, \cos\theta_2, \cos\theta_3) = \tag{3}$$
$$\Bigg[\frac{1}{N}N_3(\cos\theta_1, \cos\theta_2, \cos\theta_3) + 2\frac{1}{N^3}N_1(\cos\theta_1)N_1(\cos\theta_2)N_1(\cos\theta_3)$$
$$-\frac{1}{N^2}N_2(\cos\theta_1, \cos\theta_2)N_1(\cos\theta_3) - \frac{1}{N^2}N_2(\cos\theta_2, \cos\theta_3)N_1(\cos\theta_1)$$
$$-\frac{1}{N^2}N_2(\cos\theta_3, \cos\theta_1)N_1(\cos\theta_2)\Bigg] \times \left[\frac{1}{N^3}N_1(\cos\theta_1)N_1(\cos\theta_2)N_1(\cos\theta_3)\right]^{-1}$$

Figure 1 shows the two particle correlation function for grey particles emitted in Mg-Em interactions at 4.2 A GeV/c. The correlation function $R_2(\cos\theta)$ is measured so that the two particles are emitted within a small angular interval $\Delta\cos\theta = 0.05$ about the considered angle.

A clear signal of positive correlation is observed only for the backward emitted particles. In fact this signal has no substantial value, since the cross section of emission of gray particles at this angle is very weak as appears from Fig. 2. Nevertheless, this backward signal may be interpreted as the so called side splash effect; the region of the occurrence depends on the temperature of the domain from which the gray particles are emitted. The results of the thermodynamic model [2] showed that the angular distribution of the gray particles is strongly correlated to their emission energy, so that fast energetic particles are emitted in the forward direction from domains characterized by high temperature. Accordingly, it is reasonable to interpret results of Fig. 1 as the increase of the value of the two particle correlation function toward the colder domain, and a true signal is recorded at the coldest



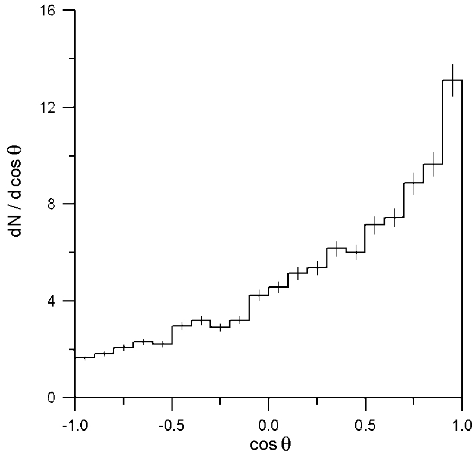


Fig. 1 (left). Two-particle correlation function $R_2(\cos\theta)$ for g-particles emitted in Mg-Em interactions at 4.2 A GeV *projectile energy. The function $R_2(\cos\theta)$ is measured so that the two particles lie in an interval $\Delta\cos\theta$ about $\cos\theta$. The error bars are considered as compound errors.*

Fig. 2. Angular distribution function for g-particles emitted in Mg-Em interactions at 4.2 A GeV *projectile energy. The error bars represent the standard deviation.*

zone corresponding to the extreme backward emission. The emission of particles from a collectively excited state of the nucleus as a Fermi liquid drop can occur in two ways. First, due to the relaxation processes where the collective energy is transferred to the intrinsic degrees of freedom with subsequent evaporation of particles. On the other hand, a direct non-statistical emission (splashing) of nucleons is also possible via the dynamical distortion of the Fermi surface accompanying the collective motion. In general, the relative contributions of these mechanisms depend upon the magnitude of the nuclear friction coefficient. The limiting cases of the direct (non-statistical) particle emission from the non-damped giant multipole resonance (GMR) and the particle evaporation from the heated nucleus may also be considered. The direct particle emission from the GMR has been extensively studied within pure quantum mechanical approaches [15, 16]. Particles emitted from excited nucleus due to both the evaporation and the splashing (emission from a cold vibrating nucleus) are due to the collective motion of the nuclear Fermi liquid and are accompanied by direct non-statistical emission of nucleons via the dynamical distortion of the Fermi surface, so they are responsible for the presence of the short range correlation.

The results in Fig. 3 show that the three-particle correlation function has strong negative correlation in the backward direction. This means that the short-range correlation is observed only among two particles and not among three gray particles. This means that the splashes that come out from the cold nuclear medium are emitted in a fine form.

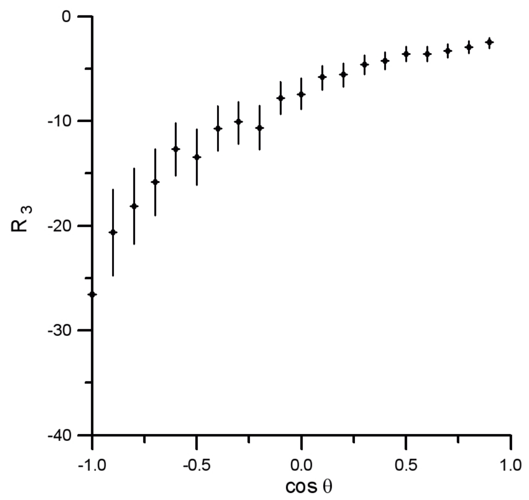


Fig. 3. Three-particle correlation function for g-particles emitted in Mg-Em interactions at 4.2 A GeV *projectile energy. The function $R_2(\cos\theta)$ is measured so that the three particles lie in an interval $\Delta\cos\theta$ about $\cos\theta$. The error bars are estimated as compound errors.*

4. *Conclusive remarks*

- Singly-charged particles with energy in the range $40 \le E \le 400$ MeV appear as gray particles in the nuclear emulsion track detector.

- Most of the gray particles are emitted as decay of fireballs. Their energy depends mainly on the temperature of the domain where the fireballs are produced.

- The low-energy gray particles are emitted in the backward direction with small cross section, and show clear signal of the two particle correlation.

- The emission of slow gray particles is either due to the relaxation processes when the collective energy of excited nucleus is transferred to the evaporated particles, or due to the splashing and direct non-statistical emission of nucleons.

- Emission of slow gray particles is also possible from the non-damped giant multipole resonance.

Appendix. Terminology

Nuclear emulsion: It is simultaneously used as the nuclear detector and the target. It displays traces during the passage of charged particle through it. It is considered as a complex target formed by two groups of nuclei, a light group (C,N,O) with an average mass number equal 14, and a heavy one (AgBr) with average mass of 96, in addition to the hydrogen nuclei.

Grey particles: They are the medium-ionizing particles that appear in grey colour in emulsion detectors, with the relative ionization density between 1.4 and 2. These particles are identified as knocked out protons.

Shower particles: Fast particles produced in emulsion detectors, mainly pions, having ionization density < 1.4.

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VIŠEČESTIČNE KORELACIJE SIVIH ČESTICA EMITIRANIH U SUDARIMA JEZGRA–JEZGRA

Proučavamo korelacije kratkog dosega izbijenih nukleona u sudarima teških iona radi upoznavanja dinamičkih značajki tih reakcija na visokim energijama. Razmatramo dvo- i tro-čestične kutne korelacije emitiranih sivih čestica iz kolektivnih uzbudnih stanja jezgre promatrane kao Fermijeva kapljica tekućine. Pozitivna se korelacija opaža samo u smjeru prema natrag što odgovara najhladnijem području jezgre. To se tumači kao izravna nestatistička emisija (zapljuskivanje) nukleona putem dinamičkog izobličenja Fermijeve površine pri kolektivnom gibanju u jezgri.